Z. Säugetierkunde 54 (1989) 172–190

ISSN 0044-3468

The external forces and internal stresses in the feet of dressage and jumping horses

By H. Preuschoft

Funktionelle Morphologie, Anatomisches Institut, Ruhr-Universität Bochum

Receipt of Ms. 13. 10. 1987

Abstract

From motion pictures taken at 200 f/s over standardized distances we measured the movements performed by the joints of horses in dressage gaits and in jumping under saddle in two dimensions. Velocities and accelerations of the whole body and its segments were calculated. With segment masses taken from the literature, the "external" forces acting on the segments were computed. The results obtained this way are in principal agreement with the accelerations and reaction forces measured during the same movements. The forces exchanged between the horse's body and the ground are mostly 2 times, sometimes up to 4 times body weight, but distributed over several extremities and fairly long time intervals. The reaction forces transmitted by a single limb in take-offs for, and in landings after a jump, but also in the dressage gaits called by Germans "starker Trab" and "starker Galopp" may lead to stresses beyond the presumed breaking strength. This in particular, if the positions of the distal extremity segments are suboptimal.

Introduction

In mammals, the shape of the body is dominated by the locomotor apparatus. Therefore we have to look after the locomotor behavior, if we wish to understand the reasons for the development of a certain body shape in an animal. This idea is by no means new, but a truly satisfying basis for the recognition of the causal relationship between form and mechanical function has been established as late as 1935–1964 by the orthopedist F. Pauwels (see also 1965). Kummer (1959) has applied Pauwels' principles to the body shape of mammals, and Preuschoft (1969, 1970a, b, 1973, 1979, 1988; Preuschoft et al. 1986) has continued this line by explaining details of primate skeletal morphology in terms of mechanics.

These considerations, however, are restricted to "long term stresses", that is, they are focussed on static situations and do not imply the time factor – neither as resistence against being moved (mass inertia), nor as the variation of external forces during time, which lead to "short term stresses".

Now we can raise new questions:
- Which stresses do occur in parts of the animal's body in more rapid movements?
- Is the shape of the element suited to sustain these stresses?

The parameters essential to answer these questions are the resultant forces acting in the joints, and the stresses in the bones. Both can not be measured directly without negative influence on the moving system. In addition, direct measurements of the strains inside the moving body are difficult to obtain, and the procedure to get them is noxious to the animal. So we used a combination of indirect approaches to obtain these values.

Our mechanical analyses are based on d'Alemberts' principle, according to which movements can be analysed as sequences of phases in which equilibrium exists between the activity of muscles on one side and the mass inertia of body segments on the other. Inertia tends to keep mass elements in their state of movement, and exerts a force which resists any change of direction or velocity. The forces caused by inertia depend on the masses of the involved body segments times their accelerations.

U.S. Copyright Clearance Center Code Statement: 0044-3468/89/5403-0172 $ 02.50/0

We used the following data: masses of segments, and either the displacements in space of body segments over time (in the form of film recordings), or the forces which act on the animal's body (force plate recordings), or accelerations of segments (data from accelerometers).

To secure the relevance of the analyses, we also need information about the biological importance of the analysed movement. The simplest and most reliable criterion seems to be the statistical frequency of its occurrence. There is considerable uniformity of opinion that frequent, though low stresses exert a decisive influence on the shapes of bones and tendons, while greater stresses, which occur less frequently, may have a higher threshold. Very rare stress patterns, which are evoked in long intervals may fall outside the "average biomechanic situation" to which the body shape is adapted (see for instance Amtmann 1979; Oxnard 1979; Preuschoft 1979, 1985). It seems safe to start from the assumption that the locomotor apparatus of an animal is adapted to sustain even the highest among the "usually", or "normally" occurring stresses. Therefore we first have to determine the "normal" loading pattern of the skeletal and tendinous elements, evoked in movements, which are executed often and without inflicting damage to the animal. The highest among the (statistically defined) "normal" stresses should encompass what the animal's body can sustain. On the same basis, we can define those situations, in which the stresses reach critical values.

Motion analyses in some cases also allowed us to approach the question how the proportions of and the mass distribution in the body fit to the pattern of locomotion (Cartmill 1974; Alexander et al. 1979; McMahon 1984; Jungers 1984, 1985; Preuschoft and Demes 1984, 1985; Peters and Preuschoft 1984; Demes and Günther 1988; Demes et al. 1988).

For studies of the type described above, the outstanding subjects are, aside from humans, horses. This because of various reasons:

- They show (and seem to be designed for) a limited variation of movements;
- these are largely restricted to only two dimensions;
- they can be reproduced reliably, in particular if performed under a rider;
- the animals are big and strong enough to carry the measuring equipment without disturbance of their movements.

In the focus of our interest have been the most specialized body segments: the "foot" in an anatomical sense, that is carpus, tarsus, metapodials and phalanges. These parts are under immediate influence of external forces, and in addition the experience of horsemen tells us that these parts are loci of predilection for failure.

Material and methods

The investigations were made with successful and high class dressage (1), event (2) and jumping horses (6) from the stable of the Deutsches Olympia-Kommittee für Reiterei (DOKR), Deutsche Reiterliche Vereinigung (FN) in Warendorf; one dressage horse owned by O. Rhode, Oer-Erkenschwick. Preliminary experiments to optimize the techniques have been made on the 2 German saddle horses of H. Dallmer, Arnsberg, and most of them on my own lightweight hunter of Irish origin. All these horses are trained according to the German dressage method. Therefore I also use the terminology usual in this country for the investigated gaits (see, for instance, Podhajsky 1968).

1. A Philips three dimensional accelerometer (PR 9369/50) with an own frequency of 3000 Hz was fixed to the saddle, close to the presumed center of gravity of the system: horse + rider (fig. 1). Its signals were telemetered through a transmitter in a saddle bag. The recieved signals were controlled on an oscilloscope and stored on a tape recorder. For evaluation, the recordings were plotted on a 6 channel printer at a paper velocity of 100 mm/s.

2. Deformations of the hoof during movement were measured with strain gages attached to the external surface of the hoof (fig. 2), and by strain gages on a spring steel band connecting medial and lateral margins of the hoof (fig. 3). The signals were transmitted through wires to the saddle bags, and recorded as before.

Unfortunately, only a small portion of these measurements could be taken synchronously with other recordings.

3. Measurements of the vertical and sagittal ground reactions by means of a home-made, triangular force plate, fit into a 7 m × 0,6 m wooden platform allowed at least in some cases a control of the ground-foot-forces obtained by calculations. The force plate recordings are very similar to those obtained from hoof deformations. There were, however, no means to calibrate the deformations of the hooves against the transmitted load.

4. High speed films were taken by the Institut für den Wissenschaftlichen Film, Göttingen at 200 f/s. The joints of the horses were marked with water-soluble colours. At constant distance of 60 m from the camera, a course of 32 m (dressage) and 48 m (jumps) length was staked out by red and white poles in 2,0 m (dressage) and 3,0 m (jumps) distance (for more details, see Preuschoft et al. 1987). The bases of these poles were connected by a red and white ribbon to indicate the horizontal. The riders were instructed to go as close to the poles as possible. The distances of the tracks from the rails turned out to vary by not more than 0.3 m.

Kinematic parameters, such as speed, stride length, frequency, duration of swing and stance phase, width and duration of suspension, angle of limb axis, path of accelerometer and other points were investigated statistically (for details see Preuschoft et al. 1987). Cycles and jumps which represent average values of these parameters were selected for digitizing.

5. Horse plus rider form a kinematic chain of 26 rigid links. The vertical and horizontal displacements of the joints were plotted against time, thus yielding the translatory and rotatory velocities of the segments.

By differentiation of the velocities we arrive at their accelerations. Resistence to being moved is given by the forces of inertia (= acceleration times mass). These forces have been calculated for each time interval. Segment masses are taken from Plagenhoef (1979).

The forces calculated for the segments in vertical, sagittal and rotatory direction are summed up. The only points through which forces can be transmitted from the ground to the animal's body are the hooves.

As long as no rotation takes place, rotating moments about the center of gravity must be zero. Therefore in phases with two hooves on the ground an exact distribution of the vertical (but not of the horizontal) components on the limbs is possible. In phases with 3 or 4 limbs in ground contact, we distributed the components so on the footing limbs, that the resultant reaction force is more or less parallel to the metapodials, because this minimizes the bending moments. Under the assumption that the forces are concentrated on the middle of the hoof, the rotating moments of the resultant external force at the interphalangeal and metapodial joints can be calculated (fig. 4). This was done only for those phases in which the external forces assume their highest values.

6. Maintenance of equilibrium at the joints requires tensile forces in the tendons and ligaments of the foot. From the external force acting against the hoof and the tensile forces in the tendons result compressive forces and bending moments in the phalanges and metapodials (as shown in fig. 2). Cross sections of the joints and metapodia, as well as lever lengths are as in Preuschoft and Fritz (1979).

Results

Some parameters, such as stride lengths and frequencies show surprisingly little variation within the cycles of one run, within the runs of one horse, and from one horse to the other (table 1). This is, however, not more than a confirmation of common knowledge, on which the internationally used principles of judging horse shows are based.

Other gait parameters, such as accelerations, or heights reached by the distal limb segments during swing phase, or strain of the hooves, or the measured intervals of force exchange vary considerably (table 2) – in particular if taken from a horse running on a rough substrate.

The deformations of the external surface of the hooves show a slow increase and a steep decrease (fig. 2). This result is not identical with the recordings obtained by Bayer (1973), and also deviates from our measurements of the width of the hoof during ground contact (fig. 3). According to measurements taken on isolated hooves under a hydraulic press, the deformations are not linearly correlated with load, and show pronounced hysteresis. Since we were not able to calibrate the deformations of the external wall in the living horse, we abandoned this method.

Hoof width increases in the stance phase by 0.05 to 1.9 mm, averages are given in table 2. It reaches a plateau in the walk, but shows a clearcut parabolic peak in all faster gaits (fig. 3). The deformation of the hoof is the more pronounced the faster the horse moves, regardless

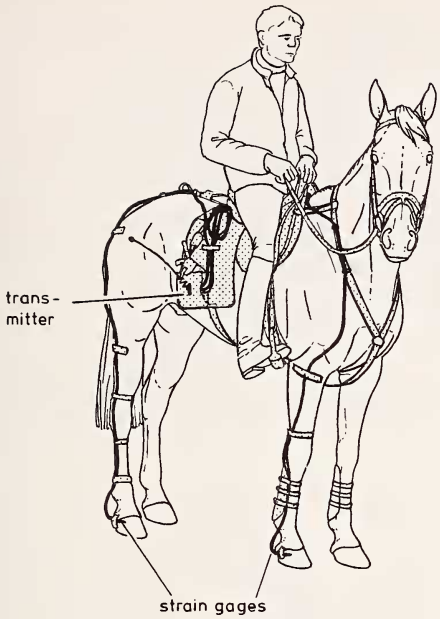


Fig. 1. Horse equipped with strain gages at right front and right hind hooves, accelerometer at saddle, teletransmitter in saddle poaches. The markings at the joints are on the left side and therefore not visible

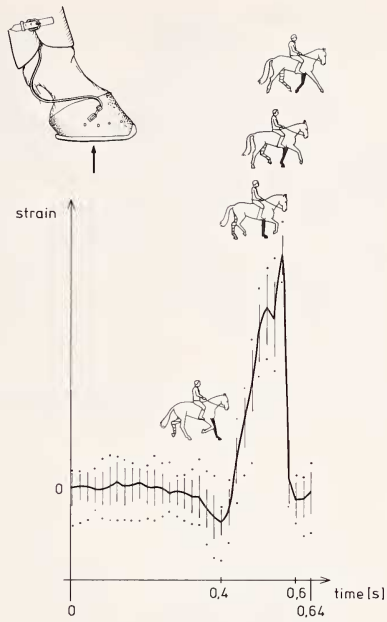


Fig. 2. Recordings of a strain gage during trot ("starker Trab"). The vertical bars crossing the graph are ± standard deviations out of 9 cycles, the dots deliminate the range of variation. The insert shows how the strain gages were attached to the hoof

Table 1. **Examples of kinematic parameters showing limited variation**

	Trot				Galop			
	x̄	sd	v.c.	n	x̄	sd	vc %	n
Cycle duration [s] „Arbeitstrab" „Arbeitsgalopp" 1 horse, 3 runs for each gait	0.75	0,03	4.12 %	126	0.64	0.03	4.69 %	180
Frequency [cycles/min] „Mitteltrab" „Mittelgalopp" 3 horses	83.90	1.50	1.78 %	28	104.80	1.70	1.62 %	60
Stride length [m] „Mitteltrab" „Mittelgalopp" 3 horses	3.48	0.15	4.19 %	76	300.50	12.02	4.00 %	120
Stride length [m] „Mitteltrab" „Mittelgalopp" 3 horses	3.43	0.15	4.23 %	28	3.19	0.12	3.60 %	60

Table 2. **Examples of kinematic parameters showing extensive variation 3 horses, 1 run each**

	Trot („Mitteltrab")				Galop („Mittelgalopp")			
	x̄	sd	v.c.	n	x̄	sd	vc %	n
Vertical acceleration [m/s²]	17.43	3.73	21.40 %	28	15.43	2.85	18.47 %	60
Horizontal acceleration [m/s²]	10.56	3.57	33.80 %	28	10.85	3.16	29.12 %	60
Maximal height front + hind hooves [cm]	24.84	2.25	9.06 %	76	25.02	2.08	8.33 %	120
Medio-lateral strain of hoof [mm]	0.43	0.13	30.40 %	23	0.38	0.15	40.06 %	41
Loading time [s]	0.34	0.04	10.75 %	69	0.28	0.02	8.63 %	82

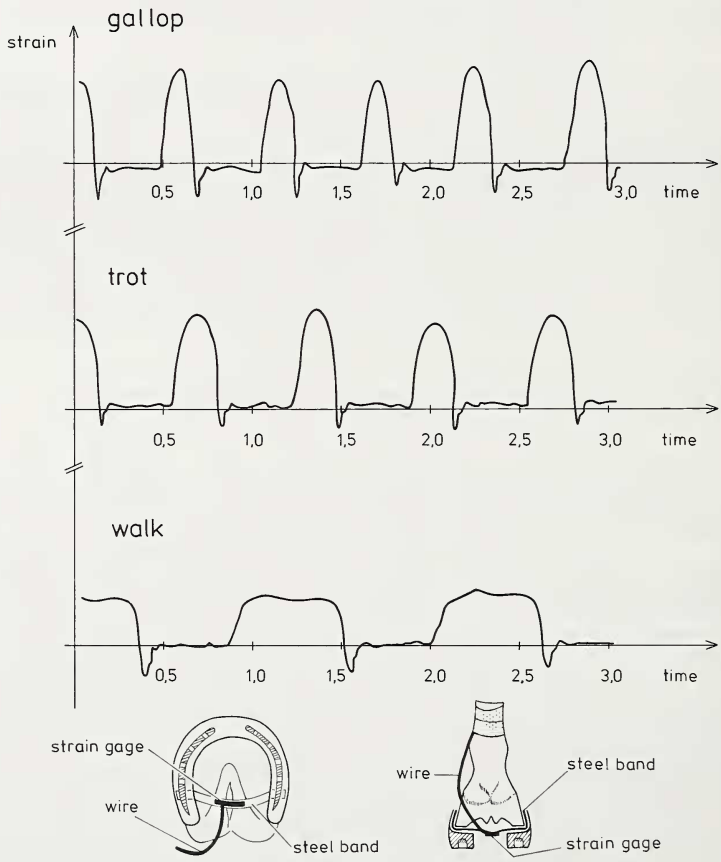


Fig. 3. Width changes over time of the front hoof in transverse direction, measured by the device shown at the bottom. It is protected by "Dallmer Hufschuh". Examples of various gaits: walk, trot, gallop on a hard substrate (concrete), same horse in all cases

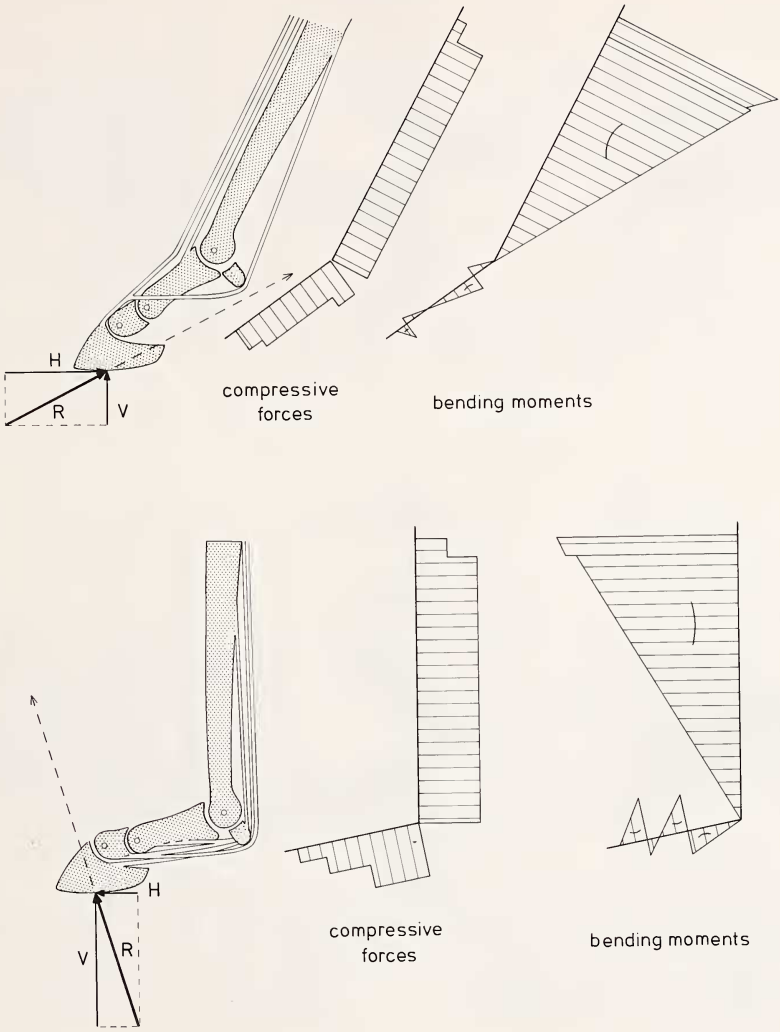


Fig. 4. Two examples to illustrate the external forces acting on a hoof. The positions of the skeletal elements and the tendons are shown, along with the respective stress patterns.
Top: early braking, hindfoot, bottom: post midstance, propelling

of the gait. In turn, the contact times, as well as the intervals of load-bearing, decrease with speed. The widths of the hoof seem to be proportional to ground-foot forces. At least these oscillograms are similar to our force plate measurements. The harder the ground, the higher the ground-foot forces, and the shorter the time of force exchange.

The period during which loads are transmitted to the ground (interval of weight-bearing) is by 0.08 s (walk), 0,06 s (trot) and 0,05 s (gallop) shorter than the electronically measured ground contact (= stance duration). The same result was obtained by comparing slow motion films with measurements, or force plate recordings.

We conclude that the animal controls and adapts the forces exchanged between body and ground to compensate for disturbances and imbalances, but avoids variation in time. By doing so it can take advantage of elastic resilience of its tendons (Dawson and Taylor

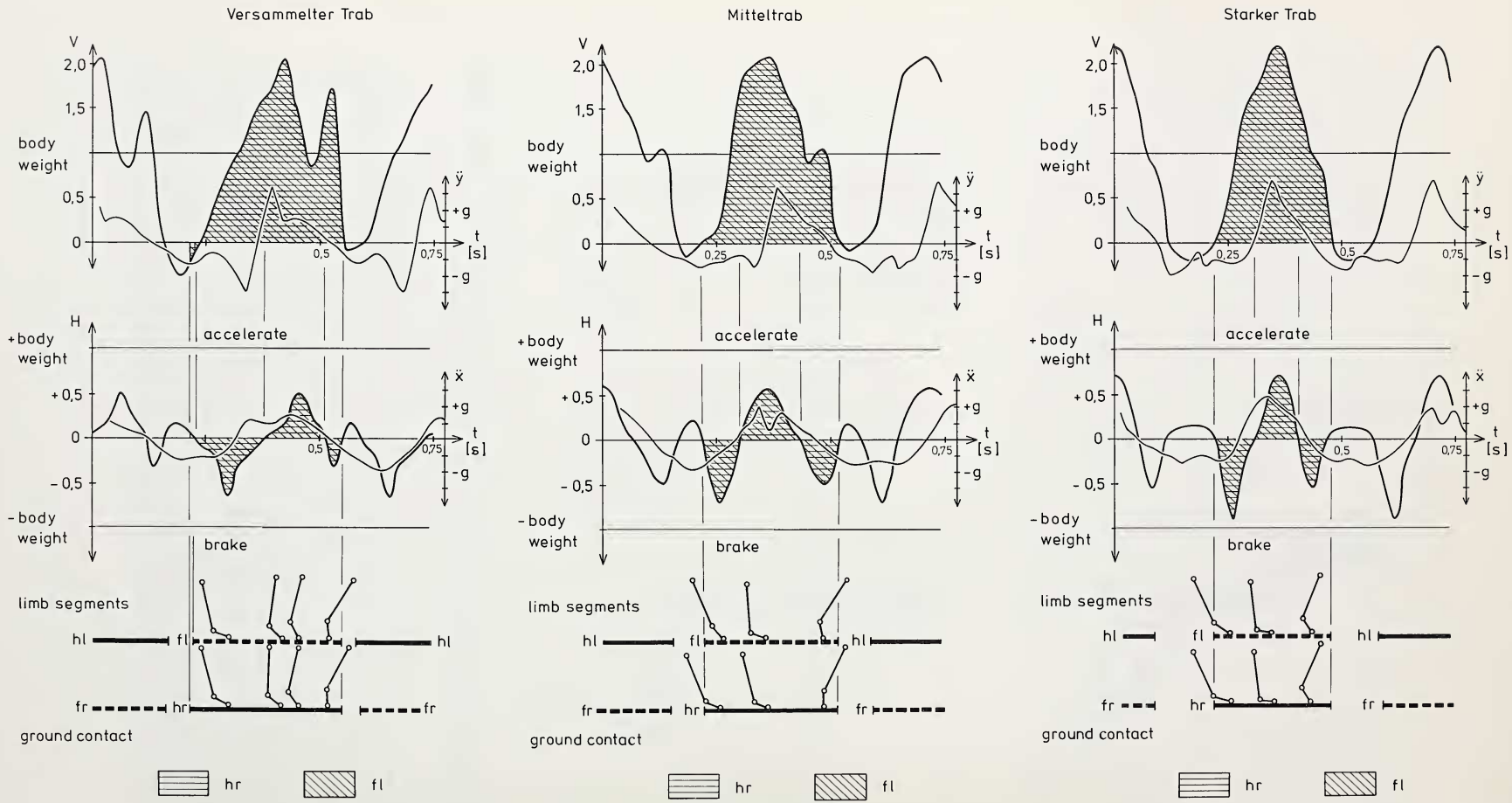


Fig. 5. Forces acting against the body of the horse trotting in 3 "tempi" (= speeds). Top row: vertical forces over time. Scales are given on left side. On the same time axis as base line, the recording of the accelerometer is shown, scale on right side. The hatching indicates support of the body by individual hooves. Middle row: braking (−) and propelling (+) on same time scale. Bottom row: the timing of footfalls and contact intervals (= stance duration). h = hind, f = front, r = right, l = left. The actual positions of the foot in critical phases of the stance period are shown as stick figures

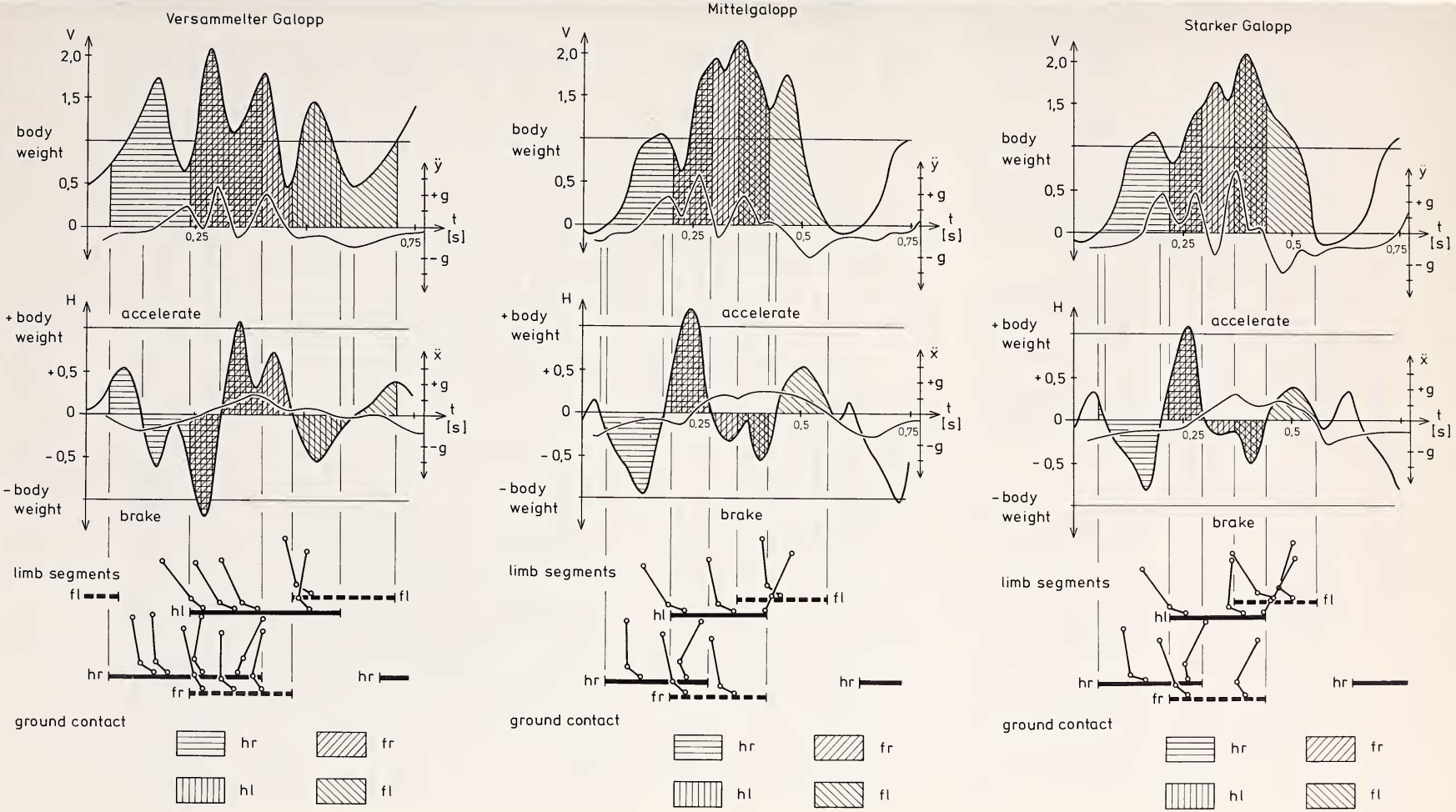


Fig. 6. Forces acting on the body of a horse gallopping in 3 "tempi" (= speeds). Arrangement and details as in fig. 5

1973; Ker 1985), which is primarily a function of time. This gives support to all ideas which interprete the locomotion of cursorial animals as a spring mechanism based on the elastic resilience of their long tendons. (Dawson and Taylor 1973; Taylor 1978; Alexander 1982, 1984, 1985; MacMahon 1984; Dimery and Alexander 1985; Hildebrand 1985).

The total forces acting on the body of the horse have been calculated for various „tempi" of the trot (fig. 5). The (larger) vertical components amount up to 2.11 times body weight (starker Trab). The calculated values coincide reasonably with the measured accelerations.

The rotations of the trunk axis indicate that in phases of support by a front- and a hindlimb ⅓ (at low speed) to ½ (at high speed) of this maximal force is carried by the hindlimb. This corresponds to the weight distribution in standing and force distribution during walking in other cursorial animals (Kimura et al. 1979). These results are also in line with fig. 7: The horizontal distances from the foot on ground to the body's center of gravity are much longer in the hindlimbs than in frontlimbs. Because of the external equilibrium, a larger share of body weight must be carried on the frontlimbs (see also riding instructions, e. g. Podhajsky 1968).

The smaller sagittal forces split into braking and propelling components. The braking forces act at the onset of the stance phase and reach higher values than afterwards. In or shortly after the middle of the stance phase, they change their sign and reach a positive maximum of 0.5 or 0.7 body weight.

At the end of the stance phase, there is a depression in the vertical, and a negative value of the sagittal force components. In these features, our results deviate from recordings of the ground reactions in horses (Biewener et al. 1983) and in other mammals (Kimura et al. 1979), in which the sagittal components use to stay at a lower level until the stance period is over, while the vertical forces do not show the ditch in their last sections.

This seems to be a consequence of the procedure we employed, namely summation of forces: At the end of the stance phase, the supporting limbs are lifted from the ground and accelerated foreward, thus exerting a "drag" on the continuously moving rest of the body.

The forces which come into action in the gallopping horse are shown in fig. 6. The vertical components can easily be interpreted as the superposition of the ground contacts of the individual feet. As in the trot, the maxima are 2–2.1 times body weight. The calculated forces agree reasonably with the measured accelerations.

The horizontal forces indicate a braking by the trailing hindlimb, which touches down first, and possibly by the diagonal hind- and frontlimb put down synchronously. Propulsion takes place immediately after the diagonal footfall, is interrupted by a second braking period which coincides with lift-off of the diagonal and touchdown of the last (leading) frontlimb. Propulsion is resumed when the body swings over the leading frontlimb. These forces do not agree with the pattern of sagittal accelerations measured at the saddle. The latter is negative until the diagonal front- and hindlimbs are put on the ground, then it becomes positive, changing its sign again during mid-stance phase of the leading frontlimb. This is the pattern of ground reaction forces which has been measured in horses (Biewener et al. 1983), smaller ungulates, monkeys and dogs (Kimura et al. 1979).

The difference between measured accelerations and calculated forces may either be due to vibrations of the saddle against the trunk or once more a consequence of the calculating procedure we have used.

The maximal forces of front- and hindlimbs are not reached at the same time. The vertical ground reactions transmitted through the frontlimbs are usually 1.4 or 2.2 times higher than those on the hindlimbs – a relationship similar to that reported above for two-limb supports in the trot.

The contact times found in the film analyses and used for these calculations differ slightly from those measured in other, less well trained horses.

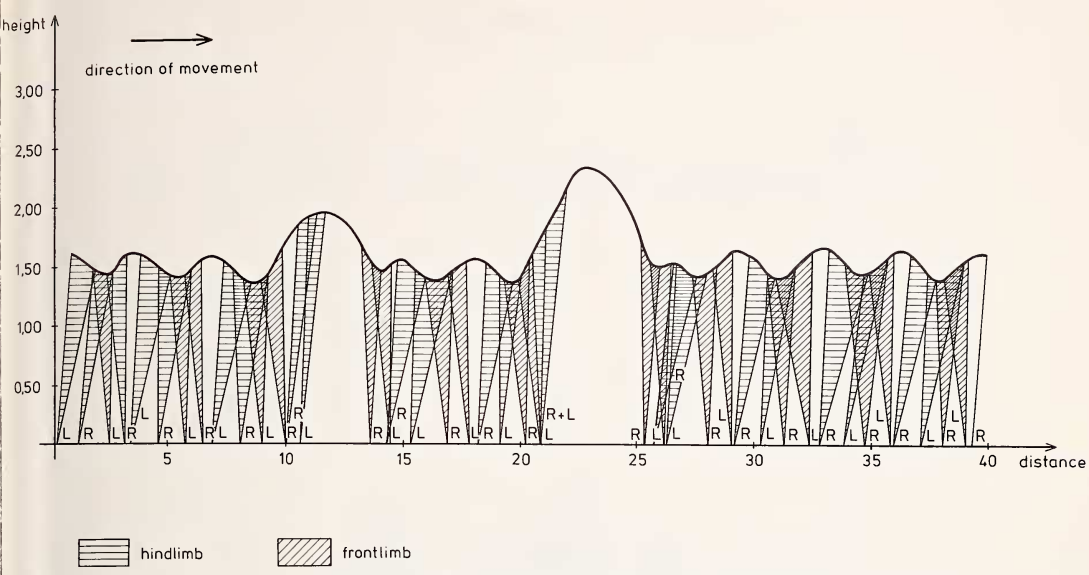


Fig. 7. Movements of a point at the saddle over support limbs. Gallop and combination of two obstacles as an example. The positions of the saddle point at touchdown and at lift-off of each limb are connected with the footing hoof. The covered angles are hatched, to show the distances over which the body travels during the stance period of a given limb

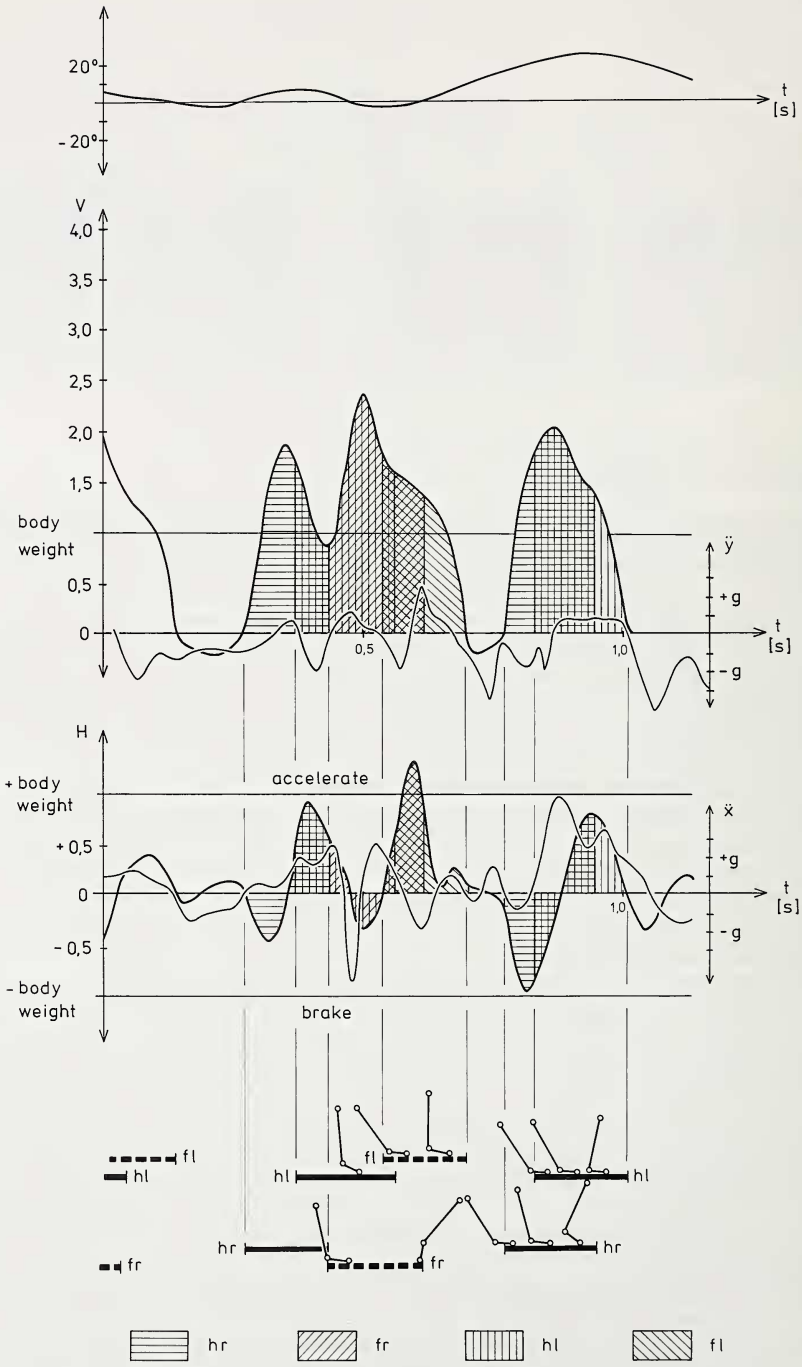
According to various parameters (Preuschoft et al. 1987), two sorts of jumps could be discriminated: high (regardless of the obstacle) and wide (over moats), (figs. 8, 9). Even in high jumps over 1.55 m, the center of gravity is lifted only 0.8 m to 0.9 m above its height in the standing horse. The apex of its trajectory is passed in jumps less than 1.20 m high before the hindlimbs lose ground contact (fig. 7). The contact intervals of the various limbs are so coordinated, that the accelerations or decelerations are distributed over all 4 extremities, and kept at a rather moderate level.

In the take-off for a broad jump (fig. 8), we find a usual gallop cycle with a vertical component going up to 2.4 body weight, that is more than in cycles on the flat. Magnitude and arrangement in time of sagittal forces are most similar to the fastest gallop, except that the frontlimbs produce more foreward propulsion. After a short phase of suspension, both hindlimbs are planted on the ground simultaneously, and exert high vertical, as well as braking, and later propelling forces.

In the high jump (fig. 9), the gallop cycle is compressed to last only 0.3 instead of 0.6 s, so that the peaks are completely fused to one hump of less than 2 times body weight. The sagittal components are as before. After a short suspension of 0.03 s the hindlimbs hit the ground, with 2.2 times body weight in the vertical, a strong braking and a smaller, though still high propelling component. In essential the same biphasic pattern of external forces has been recorded on a force plate by Alexander (1974) for a jumping dog, and by Günther et al. (1987) for a jumping Japanese macaque. Remarkable is the shortness of the take-off. We know from other leapers that a short take-off correlates with height or width (Preuschoft et al. 1979; Peters and Preuschoft 1984; Günther 1985; Günther et al. 1987). In all cases, the measured accelerations are in principal accordance with the calculated forces.

The landing is extended over more than 0.5 s. Having crossed the moat, the horse puts down one (the trailing), 0.05 s later the second (leading) frontlimb. The vertical component is less than 2 times body weight, the braking components are very high (1.0 in the first and 1,2 times body weight in the second frontlimb). The hindlimb contacts are separated by a

broad jump (take-off)



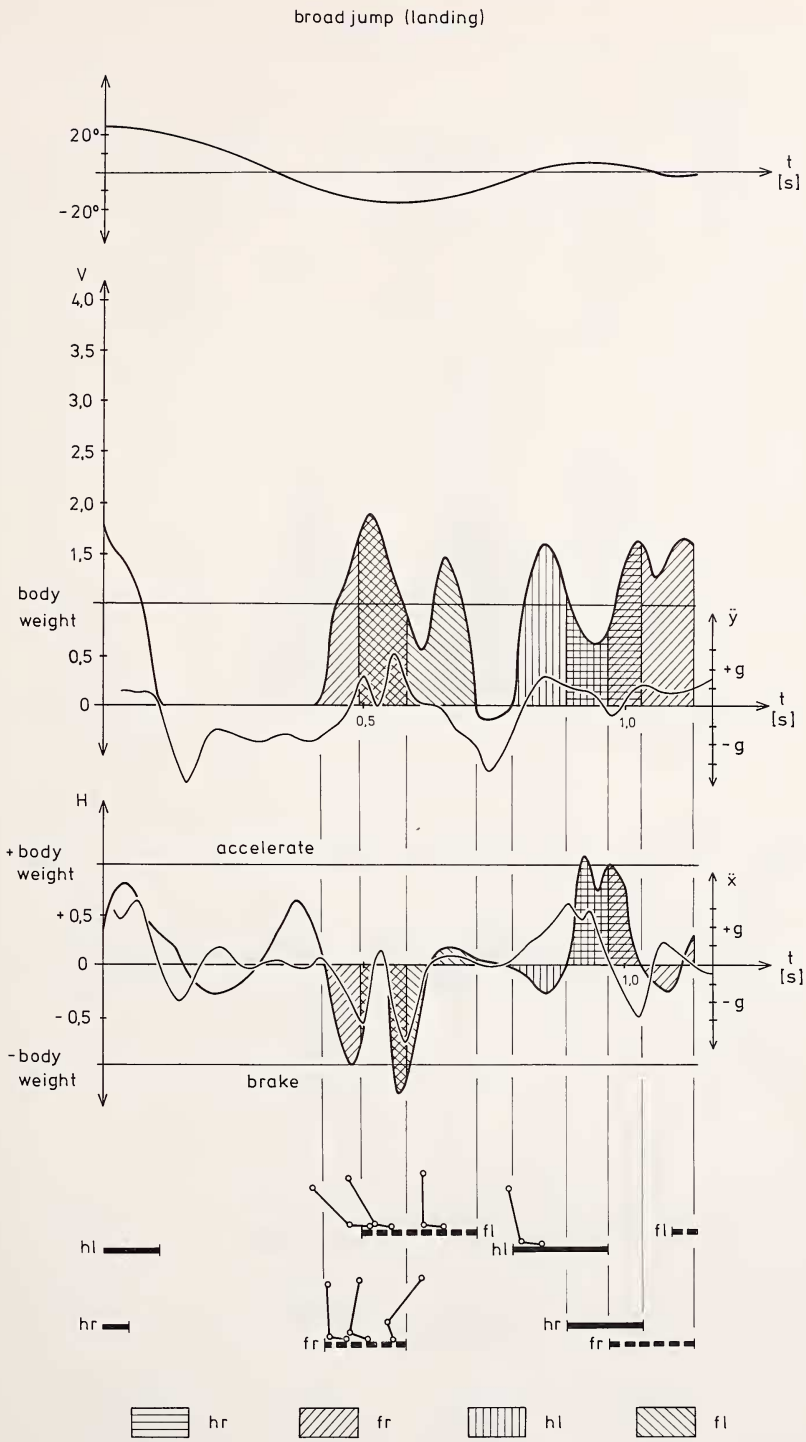
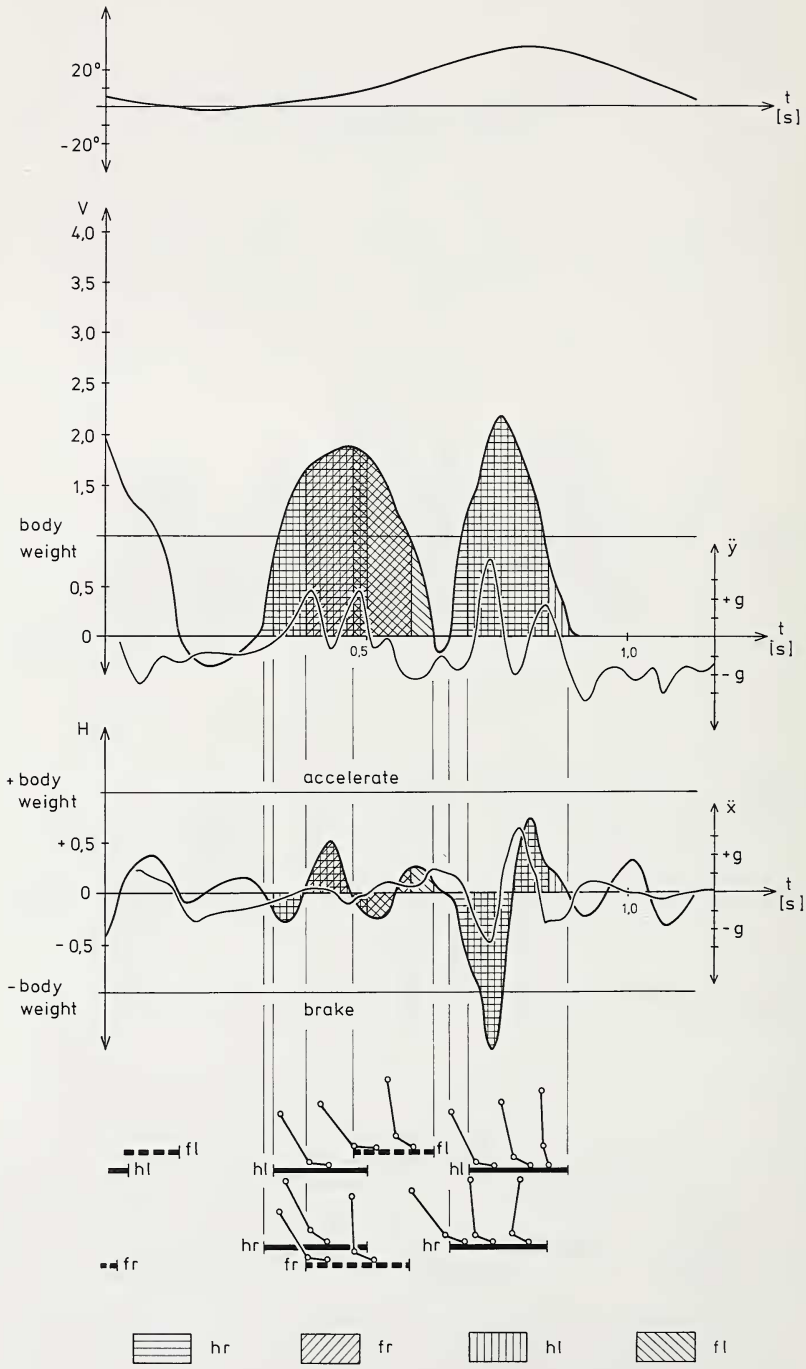


Fig. 8. Forces acting on the body of a horse in a broad jump. Arrangement and details as in fig. 9

high jump (take-off)



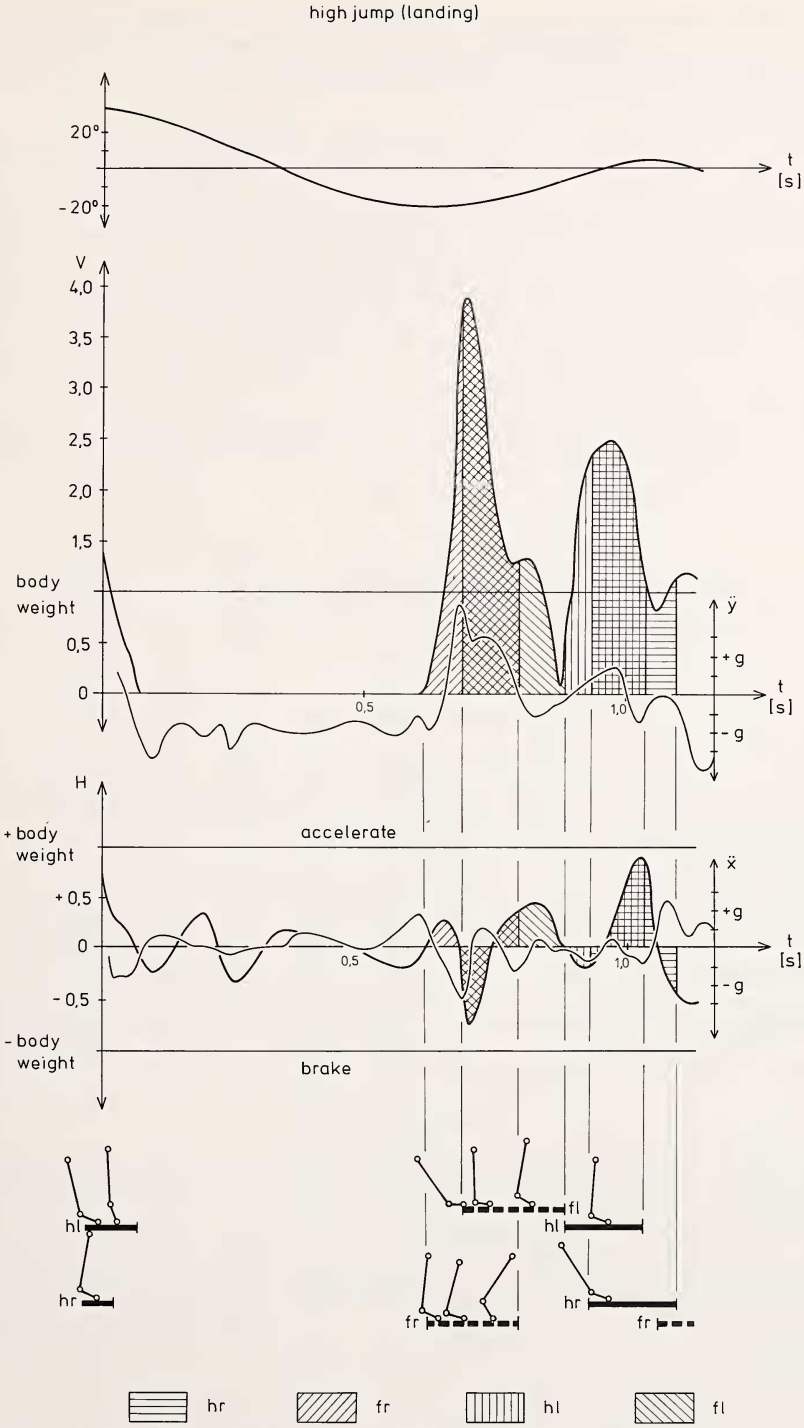


Fig. 9. Forces acting on the body of a horse in a high jump. Top row: Inclination of trunk axis. Second row: vertical forces over time. Scales are given on left side. On the same time axis as base line, the recording of the accelerometer is shown, scale on right side. The hatching indicates support of the body by individual hooves. Third row: braking (−) and propelling forces (+) in horizontal direction on same time scale. Bottom row: the timing of footfalls and contact intervals. h = hind, f = front, r = right, l = left. The actual positions of the foot in critical phases of the stance period are shown as stick figures

phase of suspension of 0.01 from ground contact of the frontlimbs, and the first pushes the body upward – just stopping tail down rotation – and then exerts, together with the second, high propulsory forces (1.1 and 1.0 times body weight). These processes are reflected in the measured accelerations.

Landings after high jumps differ from this pattern. The first (trailing) and the second (leading) frontlimb are spaced in time by 0.07 s, the vertical force transmitted being 3.85 and the braking component 0.8 body weight. In the later part of the two-limb stance, there is a reacceleration. The first (trailing) hindlimb touches down before or shortly after frontlimb lift-off, the second (leading) follows 0.05 s later. Both hindlimbs transmit another 2.4 times body weight in the vertical. While braking is minor, a forward thrust by 0.85 times body weight is produced. Again the measured accelerations coincide largely with the calculated forces.

The hooves on the ground are the only points at which external forces can be applied to the horse's body. So a combination of the calculated vertical and horizontal forces should be equivalent to the external forces acting on the hooves.

Even in the landing the damping mechanisms are so effective, that the increase of force is slow enough to exclude kinetic stress patterns, or shock waves in parts of the locomotor apparatus (Preuschoft 1985).

Table 3. **Maximal stresses found by calculation in the feet of horses** $\left[\frac{kp}{cm^2}\right]$

	Front				Hind			
Gait, tempo	Compression fetlock joint	Compression metacarpal	Bending stress proximal section of metacarpal	Total stresses	Compression fetlock joint	Compression metatarsal	Bending stress proximal section of metatarsal	Total stresses
"Versammelter Trab"	420	854	1406	1920	211	430	527	957
			−2145	−1631			−587	−157
"Mitteltrab"	397	808	2772	3580	407	830	2575	3405
			−1816	−1008			−2870	−2040
"Starker Trab"	418	850	2990	3840	421	857	2597	3454
			−2855	−2296			−2894	−2037
"Versammelter Galopp"	367	747	2350	2832	493	1003	2250	2770
			−1540	−1058			−2507	−1987
"Mittelgalopp"	332	676	2216	2892	482	980	2494	3474
			−1452	−1630			−2786	−1806
"Starker Galopp"	390	794	2210	3004	433	881	2322	3203
			−1447	−1850			−2588	−1850
Wide jump (moat) take-off	414	843	2414	2920	592	1204	2520	3201
			−1581	−1195			−2808	−2308
High jump (simple bar) take-off	278	565	2263	2828	462	940	2298	2885
			−1483	− 918			−2561	−2049
Wide jump (moat) landing	646	1313	2264	2841	518	1053	1780	2746
			−2332	−1320			−1887	− 834
High jump (simple bar) landing	817	1662	2002	2868	475	966	2571	3066
			−1312	−1565			−2867	−2372

+: compression; −: tension

For a number of phases in which the direction of the external ground-foot force is beyond reasonable doubt, we have calculated the internal forces and stresses. Out of the 84 calculations made, table 3 shows the highest values for each gait or type of jump.

Conclusions

In horses, the angles of excursion during stance phase are rather acute (MacMahon 1984; Hildebrand 1985), that means they are kept more or less in line with the large perpendicular component of the reaction force.

The decrease of the braking, and the increase of the accelerating component coincides with the swing of the extremity from anteversion to retroversion. This is a means to relieve the limbs from too great bending moments. In most cases, the compressed side of the bent foot is in front, at the side of the compression-resistent metapodial or phalanx. The extended side of the foot is at the rear, where the tendons and the interosseous medius form strong ties. Preuschoft and Fritz (1977), found that bending moments are greater in the more resistent hind- than in the less strong frontlimbs. The rudimentary second and fourth rays contribute considerably to the bending strenght of the metapodial segment. In most cases the sense of bending is foreward concave. These results are confirmed. Nonetheless, most movements imply a change of the sense of bending the metapodial.

In usual gaits of still moderate speed which are considered by riding instructions (e.g. Podhajsky 1968) as "natural locomotion" of horses, stresses reach surprisingly high values. These are hardly exceeded by the stresses found in jumps. This observation is in agreement with our recordings of accelerations, which do never show the high force peaks we calculated for landings.

Horses possess the ability to distribute the take off and the landing over long periods and over all 4 limbs, so that the stresses inside the limbs are kept within reasonable limits. Very high stresses do not only occur in jumping, but in faster dressage gaits as well.

The calculated stresses are far beyond the experimentally observed strength properties of bones. This seems to depend on our calculations, which assumed a linear increase of stresses on the cross section – an assumption which does not seem to hold true in view of recent observations on bone microstructure (Amtmann 1971; Yamada 1973; Doden 1987), although Cheney et al. (1973) have also found breaking stresses in the size order of our calculations.

In spite of this, our results show that and why a suboptimal coordination of movements, particularly in jumping horses, may become fatal: If the distal limb segments are not placed perfectly parallel to the direction of the external force, the bending stresses assume rapidly very high values which exceed the strength of the tissues.

Acknowledgements

This study was supported by the Ministerium für Wissenschaft und Forschung des Landes Nordrhein-Westfalen, Deutsche Forschungsgemeinschaft, and Reiterliche Vereinigung, Warendorf. I also wish to thank the owners and institutions mentioned in this paper for their active support and encouragement given to our work, as well as for their patience in waiting for the results. Dr. M. Fritz made the calculations, U. Nieschalk, I. Streitlein, D. Kapretz, D. Becker, K. Albert, M. Günther have contributed to the evaluation of the raw data. M. Wischniwetzki and H. Schulze have drawn the figures and H. Schepers has typed the manuscript. Without their help, the work would never have been carried out.

Zusammenfassung

Die äußeren Kräfte und die inneren Spannungen im „Fuß" von Dressur- und Springpferden

Ziel der Untersuchung ist die Ermittlung der für die Anpassung der Körperform maßgeblichen Variablen der Bewegungsabläufe. Als Beispiel für spezialisierte Läufer unter den Säugern haben wir Pferde ausgewählt. Filmaufnahmen mit 200 B/s aus konstanter Entfernung dienten zur Vermessung der Bewegungen von Gelenken und den dazwischen liegenden Segmenten in Dressurgangarten und Sprüngen unter dem Reiter. Anhand mehrerer einfacher Parameter haben wir die Variabilität der Bewegungsabläufe abgeschätzt. Die zeitlichen Verläufe und die Trittlängen haben sich als bemerkenswert konstant erwiesen, ebenso wie die Bewegungsabläufe beim Springen. Die Kräfte zwischen Huf und Boden hingegen variieren von Tritt zu Tritt beträchtlich. Die Geschwindigkeiten und Beschleunigungen des ganzen Körpers und seiner Teile wurden dann für durchschnittliche Bewegungszyklen errechnet. Unter Benutzung von Segmentgewichten, die der Literatur entnommen wurden, ließen sich die „äußeren" Kräfte bestimmen. Die so erzielten Ergebnisse stimmen recht gut mit Beschleunigungen und Reaktionskräften überein, die wir direkt gemessen haben. Die Kräfte, die zwischen dem Körper des Pferdes und dem Boden ausgetauscht werden, sind meist zweimal, manchmal fast viermal so hoch wie das Körpergewicht. Diese Kräfte werden auf mehrere Extremitäten und über längere Zeitintervalle verteilt. Die Reaktionskräfte, die beim Start vor und bei der Landung nach einem Sprung auf eine einzelne Extremität wirken, sind in der gleichen Größenordnung wie die Reaktionskräfte im „starken Trab" oder im „starken Galopp". Beide führen zu Spannungen von kritischer Höhe, insbesondere wenn die distalen Extremitäten-Abschnitte nicht in optimale Positionen gebracht werden können.

References

Alexander, R. McN. (1974): The mechanics of jumping by a dog *(Canis familiaris)*. J. Zool., London, **173**, 549–573.

— (1982): Locomotion of animals. Glasgow: Blackie.

— (1984): Elastic energy stores in running vertebrates. Am. J. Zool. **24**, 85–94.

Alexander, R. McN.; Dimery, N. J. (1985): Elastic properties of the fore foot of the donkey, *Equus asinus*. J. Zool. (London) **205**, 511–524.

Alexander, R. McN.; Jayes, A. S.; Maloiy, G. M. O.; Wathuta, E. M. (1979): Allometry of the limb bones of mammals from shrews *(Sorex)* to elephant *(Loxodonta)*. J. Zool. London, **189**, 305–314.

Amtmann, E. (1971): Mechanical stress, functional adaptation and the variation structure of the human femur diaphysis. Ergeb. Anat. Entw. Gesch. **44**, 1–89.

— (1979): Biomechanical interpretation of form and structure of bones: role of genetics and function in growth and remodeling. In: Environment, Behavior and Morphology: Dynamic Interactions in Primates. Ed. by M. E. Morbeck, H. Preuschoft and N. Gomberg. New York: G. Fischer. 183–208.

Bayer, A. (1973): Bewegungsanalysen an Trabrennpferden mit Hilfe der Ungulographie. Zbl. Vet. Med. **20**, 209–221.

Biewener, A. A.; Thomason, J.; Goodship, A.; Lanyon, L. E. (1983): Bone stress in the horse forelimb during locomotion at different gaits: A comparison of two experimental methods. J. Biomechanics **16**, 565–576.

Cartmill, M. (1974): Pads and claws in arboreal locomotion. In: Primate Locomotion. Ed. by F. Jenkins. New York: Acad. Press, 45–83.

Cheney, J. A.; Liou, S. Y.; Wheat, J. D. (1973): Cannon-bone fracture in the thoroughbred racehorse. Med. Biol. Eng. **11**, 613–620.

Dawson, T. J.; Taylor, C. R. (1973): Energetic cost of locomotion in kangaroos. Nature **246**, 313–314.

Demes, B.; Günther, M. M. (1987): Einfluß der Masse auf die Körperproportionen und den Bewegungsablauf von springenden Halbaffen. Z. Säugetierkunde., Sonderbd. zur 61. Vers. d. Ges. f. Säugetierkde., p. 13 (abstract only).

Demes, B.; Günther, M. M. (1988): Wie die Körpermasse den Springstil von Halbaffen und deren Proportionen bestimmt. Z. Morph. Anthrop. (in press).

Demes, B.; Jungers, W. L.; Nieschalk, U. (1988): Size- and speed-related aspects of quadrupedal walking in slender and slow lorises. In: Gravity in Primates. Ed. by F. K. Jouffroy and C. Niemitz. Firenze: Il Sedecesimo (in press).

Dimery, N. J.; Alexander, R. McN. (1985): Elastic properties of the hind foot of the donkey, *Equus asinus*. J. Zool., London, (in press).

Doden, E. (1987): Zur strukturellen Variation der langen Skeletelemente der Hand als Greif- und/oder Lokomotionsorgan. Verh. Anat. Ges. **81**, 253–269.

Günther, M. M. (1985): Biomechanische Voraussetzungen beim Absprung des Senegalgalagos. Z. Morph. Anthrop. **75**, 287–306.

Günther, M. M.; Ishida, H.; Ohta, M.; Kumakura, S. (1987): Behavioural adaptations towards reduction of external stresses acting on the locomotor apparatus during rapid movements, and the impact created by the take-off and landing in leaping primates. In: Gravity in Primates. Ed. by F. K. Jouffroy and C. Niemitz. Firenze: Il Sedecesimo (in press).

Hildebrand, M. (1985): Walking and running. In: Functional Vertebrate Morphology. Ed. by M. Hildebrand, D. M. Bramble, K. F. Liem and D. B. Wake. Cambridge, London: Harvard University Press, 38–57.

Hoyt, D. F.; Taylor, C. R. (1981): Gait and the energetics of locomotion in horses. Nature **292**, 239–240.

Jungers, W. L. (1984): Aspects of size and scaling in primate biology with special reference to the locomotor skeleton. Yb. Phys. Anthrop. **27**, 73–97.

— (1985): Body size and scaling of limb proportions in primates. In: Size and Scaling in Primate Biology. Ed. by W. L. Jungers. New York: Plenum Press, 345–381.

Ker, R. F. (1985): Elasticity of hand and forefoot tendons. In: "Hands". Ed. by. H. Preuschoft and D. J. Chivers (in press).

Kimura, T.; Okada, M.; Ishida, H. (1979): Kinesiological characteristics of primate walking: Its significance in human walking. In: Environment, Behavior and Morphology: Dynamic Interactions in Primates. Ed. by M. E. Morbeck, H. Preuschoft and N. Gomberg. New York: G. Fischer. 297–311.

Kummer, B. (1959): Bauprinzipien des Säugerskeletes. Stuttgart: Thieme.

McMahon, Th. A. (1984): Muscles, Reflexes, and Locomotion. Princeton, New Jersey: Princeton University Press.

Oxnard, C. E. (1979): The morphological-behavioral interface in extant primates: some implications for systematics and evolution. In: Environment, Behavior and Morphology: Dynamic Interactions in Primates. Ed. by M. E. Morbeck, H. Preuschoft and N. Gomberg. New York: G. Fischer. 183–208.

Pauwels, F. (1965): Gesammelte Abhandlungen zur funktionellen Anatomie des Bewegungsapparates. Heidelberg, Berlin: Springer.

Peters, A.; Preuschoft, H. (1984): External biomechanics of leaping in *Tarsius* and its morphological and kinematic consequences. In: Biology of Tarsiers. Ed. by C. Niemitz. Stuttgart: G. Fischer, 227–255.

Plagenhoef, St. (1979): Dynamics of human and animal motion. In: Environment, Behavior and Morphology: Dynamic Interactions in Primates. Ed. by M. E. Morbeck, H. Preuschoft and N. Gomberg. New Yorker: G. Fischer. 277–296.

Podhajský, A. (1968): Kleine Reitlehre. München: Nymphenburger Verlagsbuchhandlung.

Preuschoft, H. (1969): Statische Untersuchungen am Fuß der Primaten. I. Phalangen und Metatarsalia. Z. Anat. Entw. Gesch. **129**, 285–345.

— (1970a): Functional anatomy of the lower extremity. In: The Chimpanzee. Ed. by G. H. Bourne, Basel, München and New York: Karger. Vol. 3, 221–294.

— (1970b): Statische Untersuchungen am Fuß der Primaten. II. Statik des ganzen Fußes. Z. Anat. Entwickl. Gesch. **131**, 156–192.

— (1973): Functional anatomy of the upper extremity. In: The Chimpanzee. Ed. by G. H. Bourne. Basel, München and New York: Karger. Vol. **6**, 34–120.

— (1979): Motor behavior and shape of the locomotor apparatus. In: Environment, Behavior and Morphology: Dynamic Interactions in Primates. Ed. by M. E. Morbeck, H. Preuschoft and N. Gomberg. New York: G. Fischer. 263–275.

— (1985): On the quality and magnitude of mechanical stresses in the locomotor system during rapid movements. Z. Morph. Anthrop. **75**, 245–262.

— (1988): Biomechanical approach to the evolution of the facial skeleton of hominoid primates. Fortschr. d. Zool. Stuttgart: G. Fischer (in press).

Preuschoft, H.; Demes, B. (1984): Biomechanics of brachiation. In: The Lesser Apes. Ed. by H. Preuschoft, W. Y. Brockelman, D. J. Chivers and N. Creel. Edinburgh University Press. 96–118.

— (1985): Influence of size and proportions on biomechanics of brachiation. In: Size and Scaling in Primate Biology. Ed. by W. L. Jungers. New York: Plenum-Press. 383–398.

Preuschoft, H.; Fritz, M. (1977): Mechanische Beanspruchung im Bewegungsapparat von Springpferden. Fortschr. d. Zool. **24**, 75–98.

Preuschoft, H.; Fritz, M.; Niemitz, C. (1979): The biomechanics of the trunk in primates and problems of leaping in Tarsius. In: Environment, Behavior and Morphology: Dynamic Interactions in Primates. Ed. by M. E. Morbeck, H. Preuschoft and N. Gomberg. New York: G. Fischer, 327–345.

Preuschoft, H.; Knisel, G.; Fritz, M. (1987): Die Bewegungen von Pferden beim Springen. Warendorf: FN-Verlag, Wissenschaftl. Publikation **9**, 60–119.
Preuschoft, H.; Streitlein, I. (1987): Die Kinematik der Trabtempi bei Reitpferden. Warendorf: FN-Verlag, Wissenschaftl. Publikation **9**, 20–59.
Taylor, C. R. (1978): Why change gaits? Recruitment of muscles and muscle fibers as a function of speed and gait. Amer. Zool. **18**, 153–161.
Yamada, H. (1973): Strength of biological materials. Huntington, New York: R. E. Krieger.

Author's address: Prof. Dr. H. Preuschoft, Funktionelle Morphologie, Anatomisches Insitut, Ruhr-Universität Bochum, D-4630 Bochum 1, FRG